Fermi National Accelerator Laboratory

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Design of the D0 Overpass Dispersion Correction

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The existing D0 overpass induces a vertical dispersion wave around the Main ring with dispersion amplitudes of around 1.6 - 1.8 m. There are two major reasons to eliminate or reduce vertical dispersion induced by the D0 overpass:

- to lower the beam momentum dependence on vertical positions which had not existed before the overpass; and
- to raise the Tevatron luminosity by eliminating the dispersion mismatch between the Main Ring and Tevatron.

By definition the dispersion is a change in a particle path due to momentum difference:

$$D = p * \delta x/\delta p \qquad \ldots(1)$$

The source of dispersion is a dipole magnet where particles with higher momenta are bent less (while lower momenta particles are bent more) with a difference in the bending angle:

$$\Delta\theta = \theta_o * \delta p/p_o \ . \qquad \ldots(2)$$

The first step in the vertical dispersion bump design was to find a fast method to establish the right inputs for the SYNCH computer program which treats more accurately a transfer through elements of the accelerator. A thin element aproximation was used for the propagation of the dispersion function through all elements. This approximation made possible the use of the Floquet coordinate transformation for the dispersion function propagation. All transfer matrices (3x3) of the quadrupoles, drift space, and horizontal bends became effectively (2x2) matrices. Only the dipole transfer matrix remained (3x3) in size. The new coordinates χ and ξ are defined as:

$$\chi_i = D_i/\sqrt{\beta_i} \qquad \ldots(3)$$

$$\xi_i = \sqrt{\beta_i} * D'_i + \alpha_i/\sqrt{\beta_i} * D_i \qquad \ldots(4)$$

The Main Ring-Tevatron dispersion mismatch exists due to the vertical dispersion wave induced by the DO overpass. When the DO overpass is eliminated in the SYNCH input the resulting dispersion at the tranfer line in the Main Ring at EO is very close to the desired value.

A value of the vertical dispersion D_o in the Main Ring before the vertical bend with two Lambertsons and the slope of the dispersion function D'_o at the same place can be found from the condition that dispersion at the downstream end of the Tevatron Lambertson should be equal to zero. To have the best tranfer of both protons and antiprotons from the Main Ring to the Tevatron the slopes of the dispersion function at D49-D and at C11-A should be equal to zero. A propagation of the dispersion function, in the thin lens approximation (for protons) through the transfer line starting at the upstream end of the first Lambertson magnet, passing through the drift space between the Lambertson and the vertical quadrupole, through the quad and the drift space between the quadrupole and the Tevatron Lambertson, and finally through the Tevatron Lambertson, equals as:

$$D_o = -(2-l*q)*l\theta \qquad \ldots(5)$$

$$D'_o = q*(D_o+\theta*l)/(1-l*q) , \qquad \ldots(6)$$

where "l" is the half distance between the center of the Lambertsons (l= 768 inches), θ is the bending angle of two Lambertson magnets (θ can be found from the geommetry because the distance in height between the Main Ring and the Tevatron is 0.6477 m), and "q" is within the thin element approximation:

$$q = K^2*l_q \qquad \ldots(7)$$

where $K^2=G/(B\rho)$, G is the gradient while $B\rho$ is the magnetic rigidity. The value for q was obtained from the setting of the quadrupole made for the Main Ring-Tevatron lattice matching (the $\int B'dl=18$ kG inch/inch) $q=0.0057\ m^{-1}$. The conditions for the Main Ring-Tevatron dispersion matching are:

$$D_o = -0.625 \text{ m and } D_o' = 0.$$

There are many constraints limiting the design of the dispersion correction bumps:

1. The geometrical constraint: the dipoles must fit within the existing tunnel and the vertical kicks to the beam have to be closed:

$$\theta_1 + \theta_2 + \theta_3 = 0 \qquad \ldots (5)$$

2. Financial: to make as few dipoles of the same kind and as well as few dipoles as possible.
3. The maximum bending angle of the dipoles should not be higher than 16.24 mrad.
4. To make use of the existing drift space, etc.

Three kinds of vertical bumps have been examined during the design procedure:
1. The use of only one vertical three bump downstream of the existing D0 overpass. Given the constraint regarding the height of the central dipole of the three bump to about 30 inches above the Main Ring and the 16.24 mrad as the limiting value for the kick it was found that it is impossible to make a complete dispersion reduction with only one three bump.
2. Two three bumps, one upstream of the D0 overpass which has the last dipole placed at the drift space at C46-3, and with the second three bump downstream of the overpass beginning at the the drift space at D13-4.
3. The new overpass made by six dipoles leaving the two central dipoles of the existing four bump D0 overpass where they are with the same strengths.

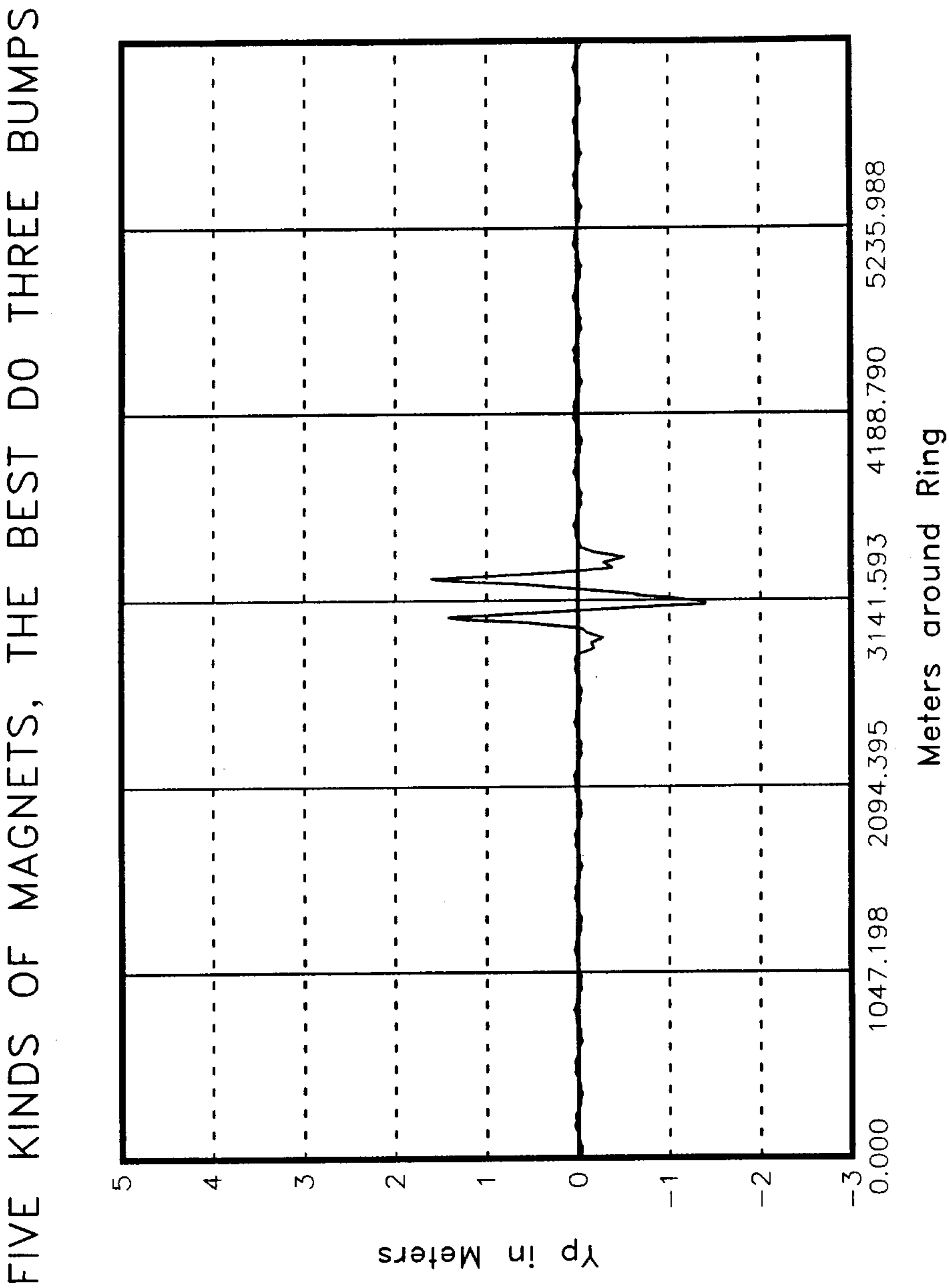
It has to be mentioned that when there is no available drift space for the vertical dipoles they could be placed in the Main Ring only after the regular horizontal dipoles are replaced by the double strength horizontal dipoles opening in this way two 6.07 m long drift spaces. Double strength dipoles have to keep the horizontal bend the same which restricts their positions at either 2-5 or 3-4 positions.

2. SOLUTIONS WITH TWO THREE BUMPS

2.1 SOLUTION WITH THE DISPERSION WAVE EQUAL TO ZERO

A solution closest to the desired conditions obtained by the thin element aproximation was used as an input for the SYNCH program. In this solution <u>all vertical dipoles within these two three bumps are of different kind</u> and the resulting vector in the χ and ξ space from all three bumps (three bump upstream of the D0 four bump overpass, D0 four bump, and the three bump downstream of the overpass) is as close to zero as possible. Figure 1 shows the SYNCH output plot of dispersions around the ring when the B0 overpass is ignored for the data obtained from the solution mentioned above.

The positions of the dipoles in this solution are: the first three bump starts at C37-5 with a kick of θ_1=4.19 mrad, C44-5 with θ_2=-17.99 mrad, and C46-2 with θ_3=13.8 mrad; the second bump



FIVE KINDS OF MAGNETS, THE BEST DO THREE BUMPS
Yp in Meters
Meters around Ring
5
4
3
2
1
0
−1
−2
−3
0.000
1047.198
2094.395
3141.593
4188.790
5235.988

Figure 1

starts at D13-4 with a kick upwards θ_4=10.93 mrad, D15-5 with θ_5=-16.39 mrad, and the last dipole is at D19-5 with θ_6=5.46 mrad (the SYNCH file name is WK 1.0).

2.2 MATCHING THE TEVATRON WITH THREE KINDS OF DIPOLES

The next two three bumps present a solution which will fulfill the condition for the Main Ring-Tevatron dispersion match (it makes a dispersion at E0 equal to D_o=-0.38 m and the slope of the dispersion function with both overpasses and correction bumps is very close to zero at both C49-D and at E11-A). At the same time this solution makes a relatively small dispersion wave around the ring (+/- 26 cm). This is also a solution with the smallest number of different dipoles because it requires just three kinds of dipoles:

1. A regular double strength vertical dipole already used in D0 and B0 overpasses which produces a kick of 16.236 mrad.

2. A vertical dipole 4.0644 m long which makes a kick of 10.87 mrad having the same current through the coils.

3. A vertical dipole 2.006 m long which makes a kick of 5.3655 mrad and it is also hooked to the Main Ring bus.

Figure 2 presents a shematic presentation of two three bumps together with the existing D0 overpass, while Figure 3 presents details of all changes within the beam lines.

The first three bump starts at C39-3&4. The center of the first dipole should be placed .539 meters doownstream of the position between magnets C39-3 and C39-4 (s=2886.5862 + .539 m) due to the exact closure. As it was mentioned above this dipole produces a kick of θ_1= 5.3655 mrad.

The central dipole of the first three bump is located at C44-5 with a kick downward of θ_2=-16.236 mrad (s=2985.3795 m).

The last dipole is placed at C46-3 (the existing drift space). The exact position of the 2 meter long dipole is 1.00 m downstream of the center of C46-3 (s=3032.1155 + 1.00 m).

The height difference between the central dipole of this bump and the Main Ring horizontal axis is 52.72 cm.

The second three bump starts at the available drift space downstream of the D0 overpass at D13-4 with the same kick as the last dipole of the first bump θ_3=θ_4.

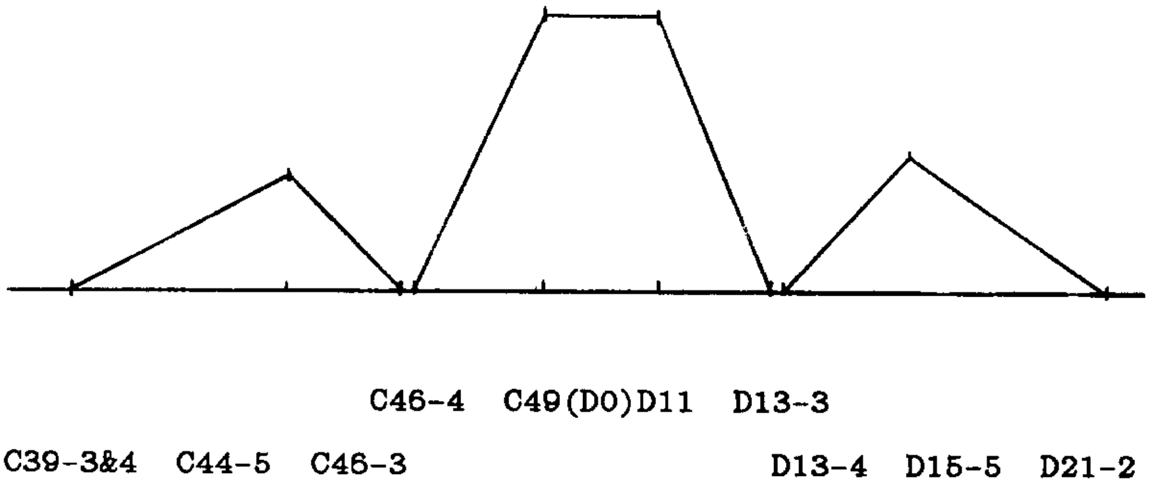
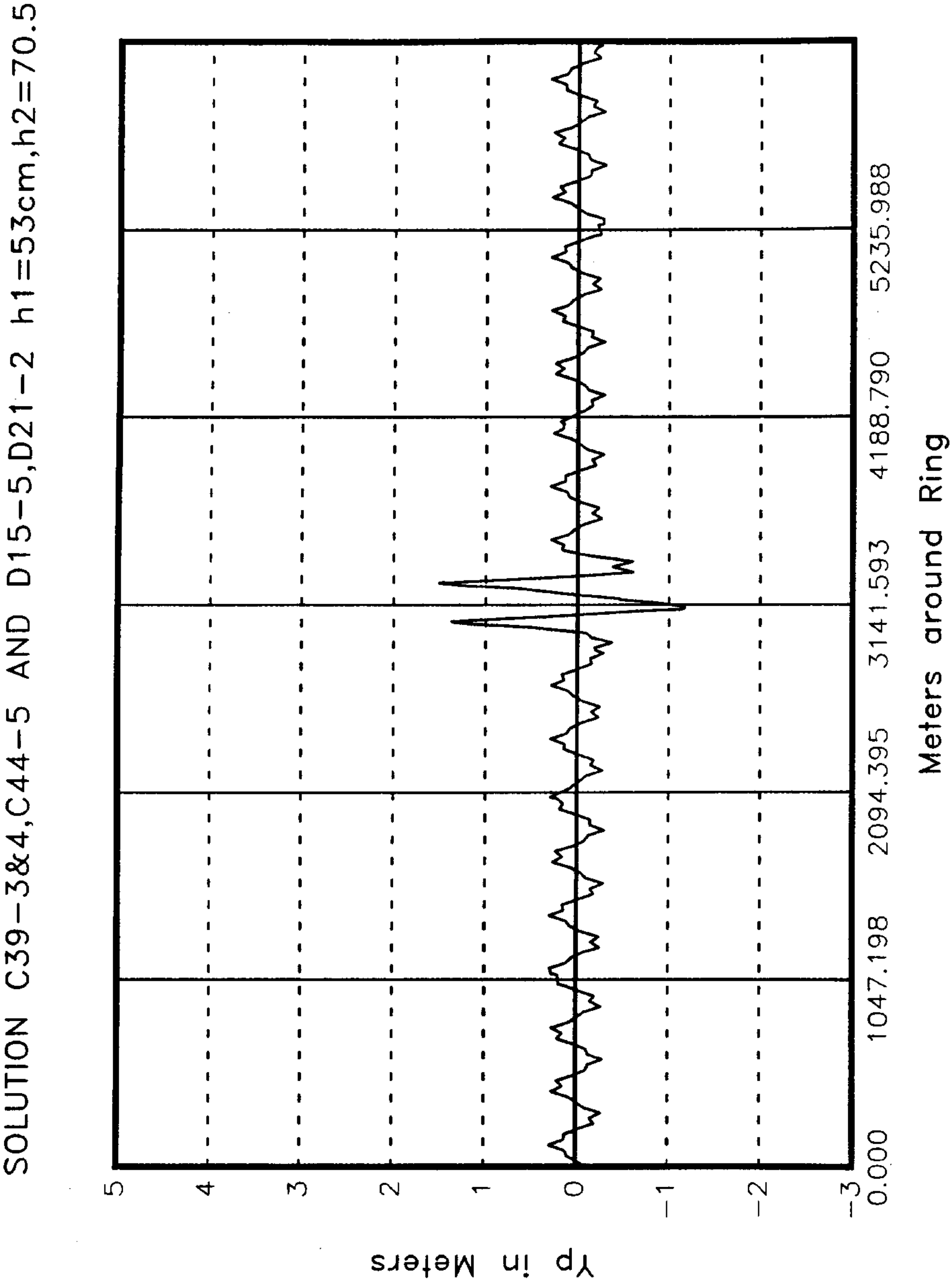


FIGURE 2. Schematic presentation of two three bumps (VB1:C39-3&4, VB2:C44-5, VB3:C46-3; VB4, VB5, VB6, and VB7 are the dipoles of the existing overpass; VB8:D13-4, VB9:D15-5, and the last dipole VB10:D21-2).

QD	DOUBLE H.	VER. DIP.	DOUBLE H.	
C39-1	C39-2	C39-3&4	C39-5	
QF	DRIFT	DOUBLE. H	DOUBLE H.	VER. DIP.
C44-1	C44-2	C44-3	C44-4	C44-5
QF	DOUBLE H.	VERT.DP.	VERT. DP.	DOUBLE.H.
C46-1	C46-2	C46-3	C46-4	C46-5
QF	DOUBLE H.	VERT. DP.	VERT. DP.	DOUBLE H.
D13-1	D13-2	D13-3	D13-4	D13-5
QF	DRIFT	DOUBLE H.	DOUBLE H.	VERT.DP.
D15-1	D15-2	D15-3	D15-4	D15-5
QD	VERT. DP.	DOUBLE H.	DOUBLE H.	DRIFT
D21-1	D21-2	D21-3	D21-4	D21-5

FIGURE 3. Changes in the beam lines for the two three bump solution with three kinds of dipoles.



SOLUTION C39−3&4,C44−5 AND D15−5,D21−2 h1=53cm,h2=70.5
Yp in Meters
5
4
3
2
1
0
−1
−2
−3
0.000
1047.198
2094.395
3141.593
4188.790
5235.988
Meters around Ring

Figure 4

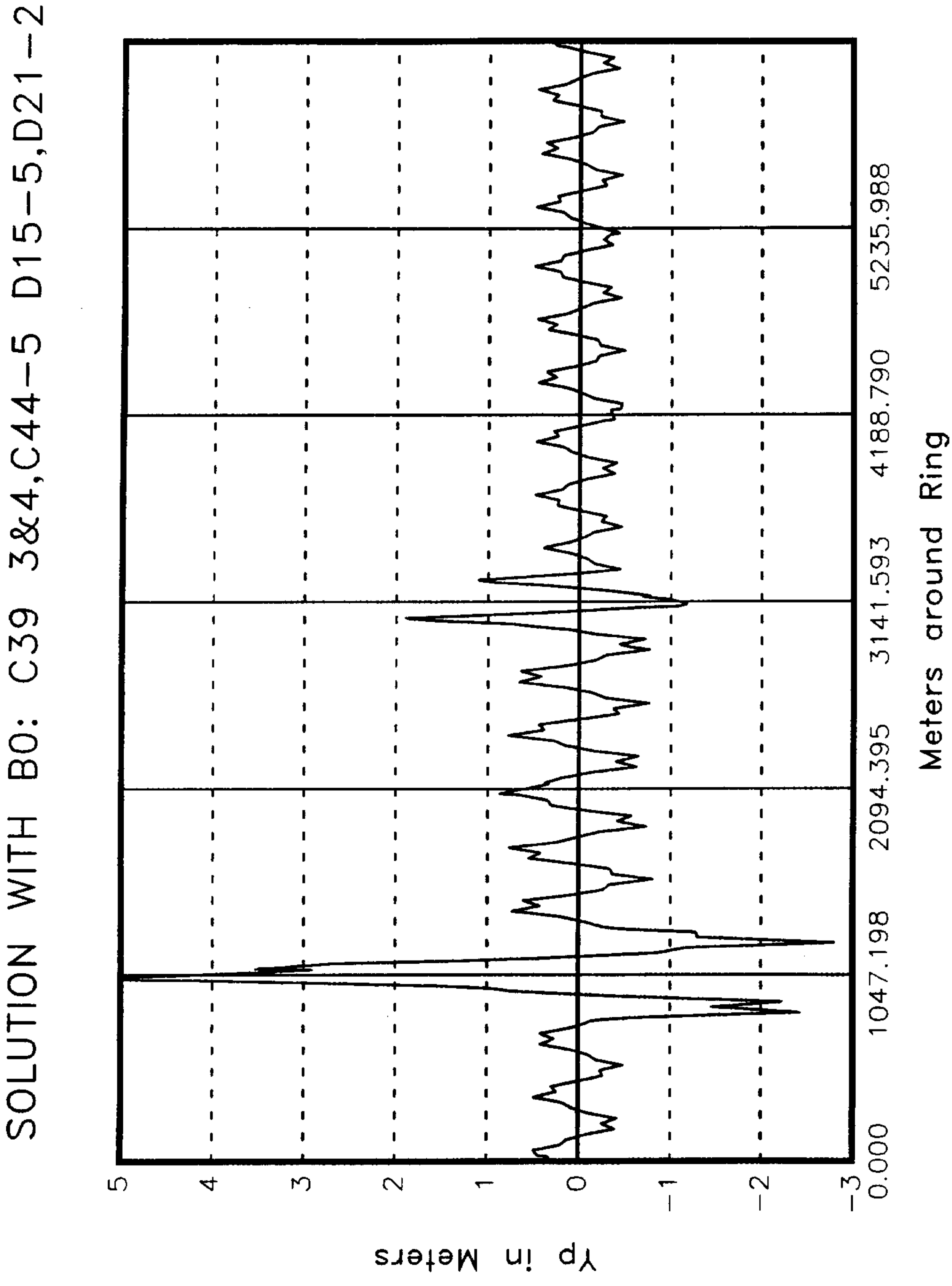

SOLUTION WITH B0: C39 3&4,C44-5 D15-5,D21-2
Yp in Meters
Meters around Ring
5
4
3
2
1
0
−1
−2
−3
0.000
1047.198
2094.395
3141.593
4188.790
5235.988

Figure 5

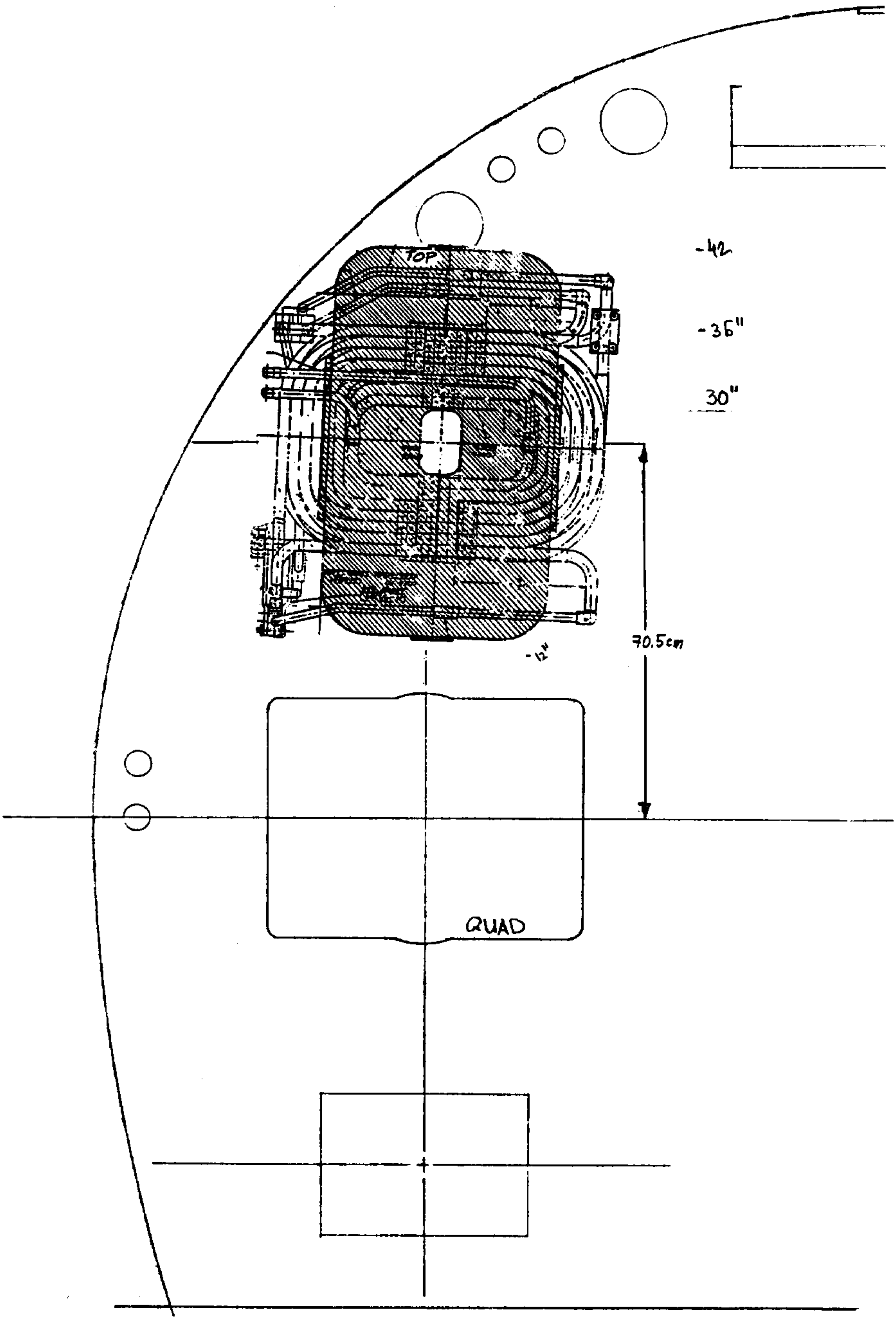


Figure 6

The exact location of this dipole is at 1 meter downstream of the center (s=3252.8732 + 1.00 m).The second dipole is located at D15-5 with the kick $\theta_5=\theta_2$ of 16.236 mrad, while the last dipole is at D21-4 with the kick $\theta_6=\theta_1$ of 5.3655 mrad (s=3318.7354 m). The height difference between the central bump and the Main Ring horizontal axis is 70.5 cm.

The exact position of the last dipole is 1.809 meters downstream of the center of the D21-2 (s=3448.3262 + 1.809 m). Actually the end of this dipole is at the same position as the end of the regular dipole of the Main Ring at this position.

Figure 4 is the output of the SYNCH program and shows the dispersion wave induced by two three bumps together with the existing DO overpass four bump but without the BO overpass.

Figure 5 presents the dispersion due to both BO and DO overpasses with two three DO bump dispersion correctors (the SYNCH file name of this solution is WKFFF_1).

The cross section of the tunnel with this highest magnet of two three bumps is presented in Figure 6.

3. SOLUTIONS WITH SIX AND EIGHT DIPOLES-NEW OVERPASS

The major constraint of this design are positions of two quadrupoles of the existing DO overpass at locations C-48 and D-12 because they are very close to the ceiling. Their height difference in respect to the main ring horizontal plane is about 65 cm.

3.1 SOLUTIONS WITH SIX DIPOLES AND SYMMETRIC POSITIONS BUT ABOVE THE CEILING AT C-48 AND B-12

3.1.1 The first solution with a total of six dipoles in the bump actually divides the existing overpass into two parts having the dispersion at the central position equal to zero. Positions of two central dipoles of the existing overpass remain the same. A new overpass starts at C37-2 with a kick upward of 3.73 mrad continues with another kick of 12.51 mrad at C48-5 righ in front of the oposite kind of a kick of the VB2 (existing C49-vertical dipole). The fifth dipole of this solution is located at D11-2 with a kick downward of 12.67 mrad and the last dipole located at D22-2 has a kick of 3.56 mrad. Two vectors presenting kicks of two central dipoles within the ξ and χ space mentioned above propagate almost along the horizontal axis ξ.

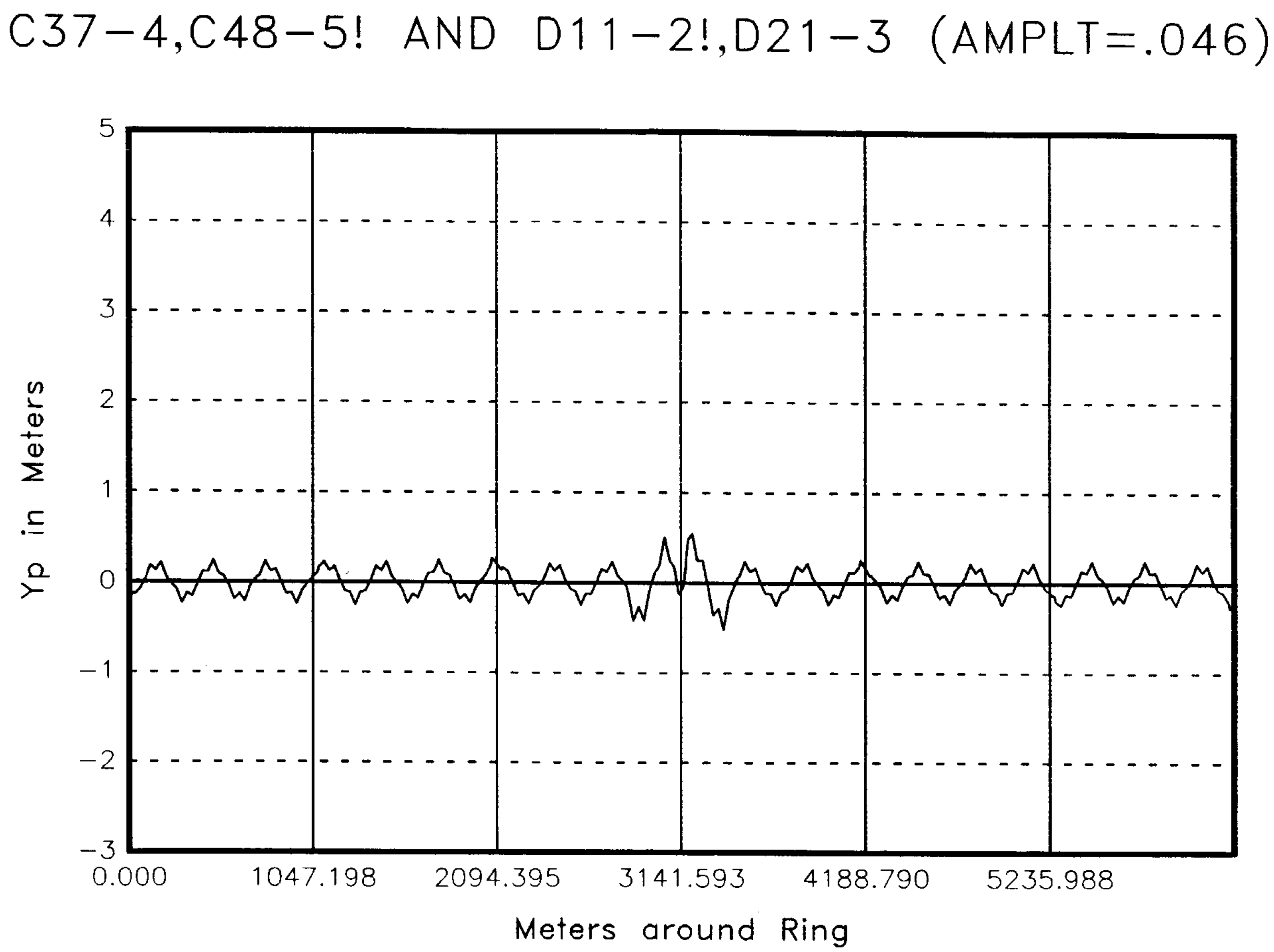
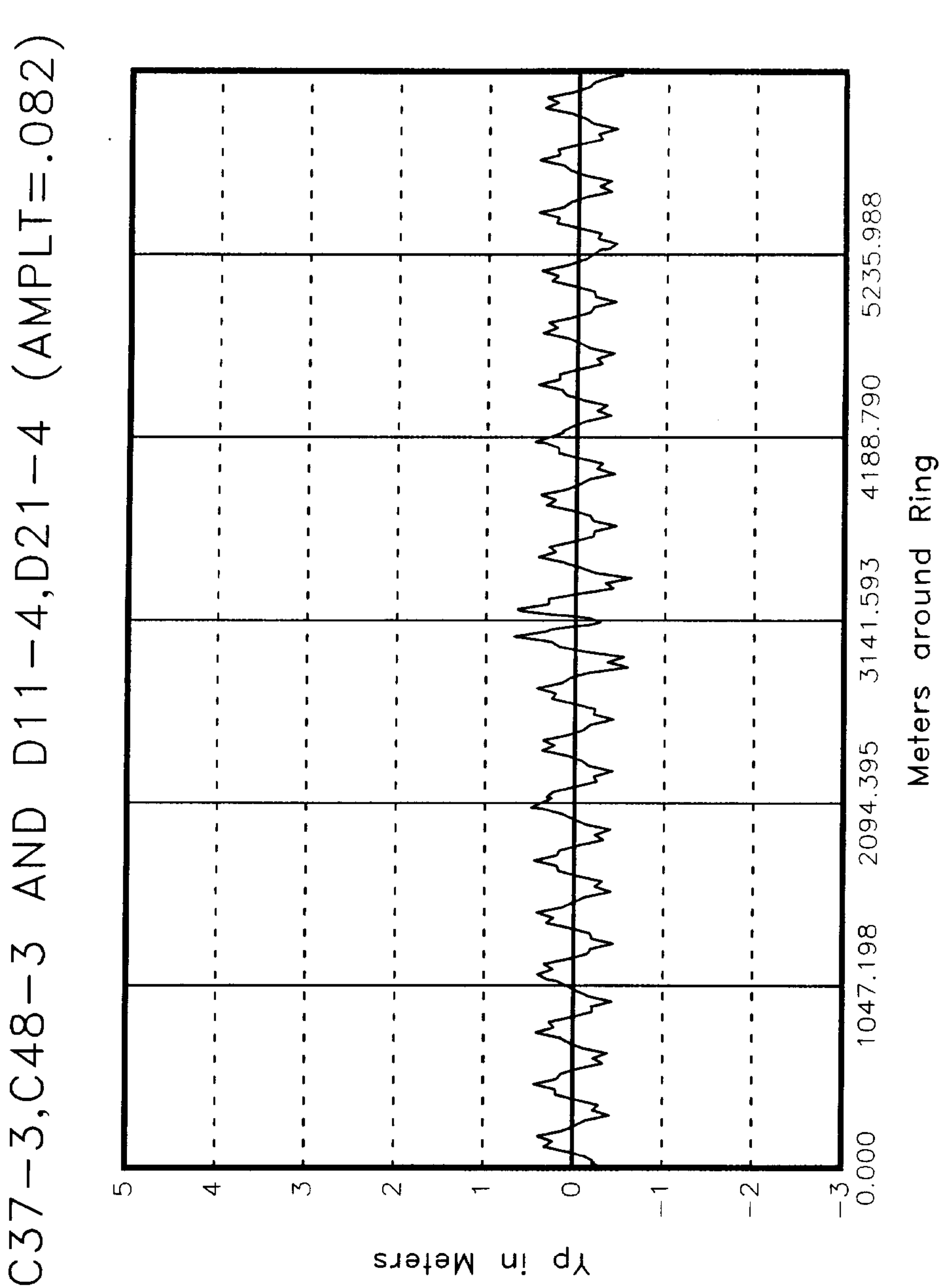

C37−4,C48−5! AND D11−2!,D21−3 (AMPLT=.046)
Yp in Meters
5
4
3
2
1
0
−1
−2
−3
0.000
1047.198
2094.395
3141.593
4188.790
5235.988
Meters around Ring

Figure 7



C37−3,C48−3 AND D11−4,D21−4 (AMPLT=.082)
Yp in Meters
5
4
3
2
1
0
−1
−2
−3
0.000
1047.198
2094.395
3141.593
4188.790
5235.988
Meters around Ring

Figure 8

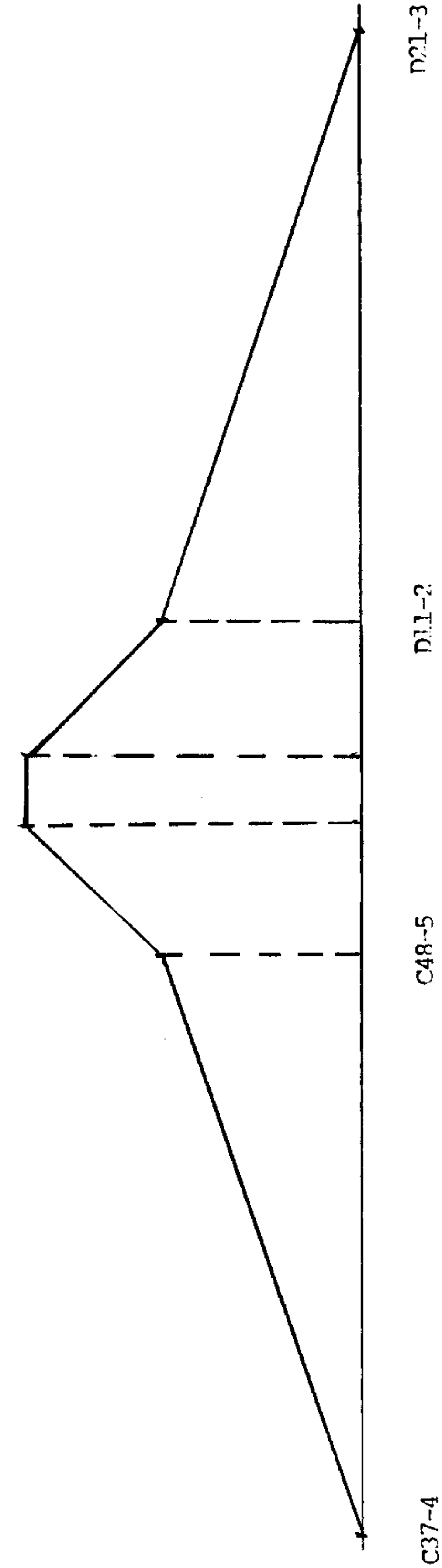


Figure 9

Figure 7 presents the SYNCH output of this new six dipoles DO overpass. In this solution positions of the quadrupoles at C48-1 and B12-1 are unfortunatelly way above the ceiling-their heights are 64 cm above the existing ones. Two dipole at C48-5 and D11-2 are at 1.063 meters above the Main Ring horizontal plane.

The C48-1 and D12-1 quadrupoles are 13.6 cm above the existing positions when the second and the fifth dipoles of the bump mentioned above are moved away of the central dipoles VB2 and VB3 of the existing overpass. In this solution the first dipole starts at C37-3 with a kick of 3.22 mrad while the second is at C48-3 with a kick of 13.01 mrad. The fifth vertical dipole downstream of the two central dipoles of the existing overpass is located at D11-4 with a kick of 13.05 mrad. The bump of this solution finishes with the last dipole at D21-4 with a kick of 3.18 mrad. The SYNCH output of this solution is presented in Figure 8.

Figure 9 presents a schematic presentation of the "six dipoles solutions".

3.2 THE BEST SOLUTION - FINAL PROPOSAL FOR A PROJECT

This is a proposal for the new DO overpass which will:

1. Establish the dispersion match between the Main Ring and Tevatron,
2. Make the dispersion around the Main Ring smaller especially within the BO overpass region.

The first step in modifying the DO overpass was to establish a design which will make dispersion around the ring equal to zero neglecting the existing BO overpass. This first solution makes the dispersion around the ring equal to zero while the dispersion values within the DO bump are smaller than 1 meter. The dispersion wave which still exists around the ring is induced by the BO overpass. Rod Gerig continued to work on the design trying to make best possible dispersion match between the Main Ring and the Tevatron and at the same time make the smallest possible values of dispersion around the ring and especially within the BO overpass. He also introduced the other tune of 19.6 into his final version of the DO overpass. He also imlemented in this design Sho Ohnuma's computer program which calculates the roll of the vertical dipoles for different radial positions of the overpass.

A schematic presentation of this final solution for the new DO overpass is given in Figure 10. This solution includes eight vertical dipoles in the bump and keeps only two central dipoles of the existing overpass at the same positions. The beam lines between the quadrupoles C48-1 and D12-1 and these two dipoles will remain the same. <u>All dipoles within this new overpass are of the same strength of 16.2356 mrad.</u>

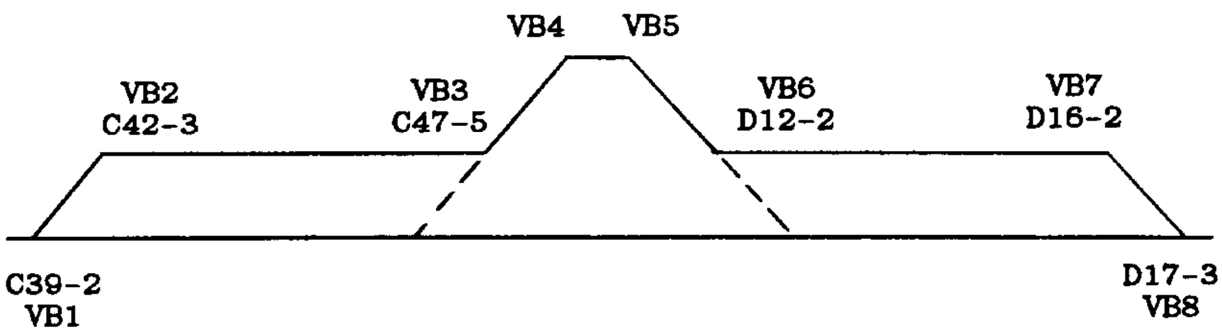


FIGURE 10.

The overpass starts with a vertical dipole VB1 placed at C39-2 with a kick upward of 16.1069 mrad. The vertical kick differs from the dipole strength because the dipole is skewed in a vertical plane by 7.16 degees, as explained later. It is also skewed in the horizontal plane by an angle equal to half of the vertical kick. The two horizontal dipoles twice stronger than the regular horizontal dipoles are at C39-3 and C39-4.Lattice changes in the beam line C39 are presented in Figure 11.

C39-1	C39-2	C39-3	C39-4	C39-5
QD	VB1	DOUBLE HOR.	DOUBLE HOR.	DRIFT

FIGURE 11. Changes in the C39 half cell.

The second vertical dipole VB2 is at C42-3 with the same kick but in the opposite direction and is also skewed by the same 7.16 degrees in the vertical plane. The two double strength horizontal dipoles are at C42-2 and C42-5. The overpass continues straight along the tunnel with 58.18 cm above and parallel to the Main Ring horizontal plane. Changes in the lattice in C42 are presented in Figure 12.

C42-1	C42-2	C42-3	C42-4	C42-5
QF	DOUBLE HOR.	VB2	DRIFT	DOUBLE HOR.

FIGURE 12. Changes in the half cell C42.

The third vertical dipole VB3 is located at C47-5 just upstream of the quadrupole C48-1 which was mentioned above. The two double strentgh horizontal dipoles are at C47-3 and C47-4, while C47-2 will become the drift space. The C47-5 vertical dipole produces the kick of 15.442 mrad upward because it is skewed dipole in the vertical plane for 17.99 degrees. It has a kick in the horizontal plane of 5.0146 mrad. Changes in the lattice in the C47 half cell are presented in Figure 13.

C47-1	C47-2	C47-3	C47-4	C47-5
QD	DRIFT	DOUBLE HOR.	DOUBLE HOR.	VB3

FIGURE 13. Changes in the C47 half cell.

The new overpass continues as the existing one along the beam line from the quadrupole C48-1 up to the existing vertical dipole VB4. The VB4 vertical dipole has the same kick as before of 15.442 mrad downward as does the VB5 dipole upstream of the D11A quadrupole.

The sixth dipole VB6 of the new overpass is located at B12-2 just downstream of the quadrupole D12-1 mentioned above. Again this dipole produces the same kick of 15.442 upwards. Two double strength horizontal dipoles are at D12-3 and D12-4. Changes in the lattice in the D12 half cell are presented in Figure 14.

D12-1	D12-2	D12-3	D12-4	D12-5
QD	VB6	DOUBLLE HOR.	DOUBLE HOR.	DRIFT

FIGURE 14. Changes in the D12 half cell.

The overpass continues straight through the tunnel with 58.143 cm above and parallel to the Main Ring horizontal plane.

The seventh dipole VB7 is located at D16-2 with the same kick downward of 16.1069 mrad. Two double strength horizontal dipoles are at D16-3 and D16-4. The beam line continues downward up to the last vertical dipole of the bump. Changes in the D16 half cell are presented in Figure 15.

D16-1	D16-2	D16-3	D16-4	D16-5
QD	VB7	DOUBLE HOR.	DOUBLE HOR.	DRIFT

FIGURE 15. Changes in the D16 half cell.

The last vertical dipole VB8 is located at the existing drift space D17-3 and has the same kick upward of 16.1069 mrad.

D17-1		D17-3	D17-4	D17-5
QF		VB8	REG.HOR.DP.	REG.HOR.DP.

FIGURE 16. Changes in the D17 half cell.

The positions of the two last dipoles are in accordance with the final solution which will fullfill requirements for the dispersion match between the Main Ring and Tevatron and at the same time give the lowest values of dispersion within the BO overpass when the tune is 19.6. It is also important to place the vertical dipoles with 3 inches horizontal apertures at locations where the horizontal dispersion is lower. This solution takes that into account by putting the vertical magnet at D17-3 where horizontal dispersion is lower.

In the first design of the new DO overpass where the dispersion is equal to zero around the ring when only this overpass is present last two dipoles where positioned at D17-2 and D18-3.

The SYNCH output of the dispersion around the ring is presented in Figure 17, where the BO overpass is not included. Figure 18 presents the SYNCH output with both overpasses included. Figure 19 presents the SYNCH output of the original design where the BO overpass is not included.

The major characteristics of the new DO overpass are:

All vertical dipoles are the same. They are connected to the same DO bus and are of the same strength of 16.2356 mrad as the dipoles already used in both BO and DO overpasses.

The new overpass is only 58.18 cm above the Main Ring horizontal plane.

The Main Ring-Tevatron dispersion match is fullfilled and values of dispersion through the BO are lowered.

If the overpass were to have the radial position the same as the rest of the ring the circumference of the ring would be longer by about 2.4 cm. As mentioned above the Sho Ohnuma's computer program implemented by Rod Gerig calculated the roll of the vertical dipoles for different radial positions of the overpass. This final proposal (Rod Gerig-the file name WD_H) makes the Main Ring shorter by 0.40 inches. It was stated that the circumference of the Main Ring should be shorter by 0.5 inches. The alignment procedure for this new overpass will be the same as for the BO overpass. Craig Moore will define correct magnet positions using the output of the program mentioned above.

TABLE 1 presents values of vertical dispersion within the BO overpass in the present situation and with corrected DO overpass.

TABLE 1 -DISPERSION VALUES (IN METERS)

LOCATION	A45	A43	A49	B12	B16	B15-3	B18
NEW DO	-1.5	-2.15	4.76	1.78	-2.05	-1.54	-0.5
PRESENT	-2.08	-0.9	4.40	3.4	-2.5	-2.0	-2.5

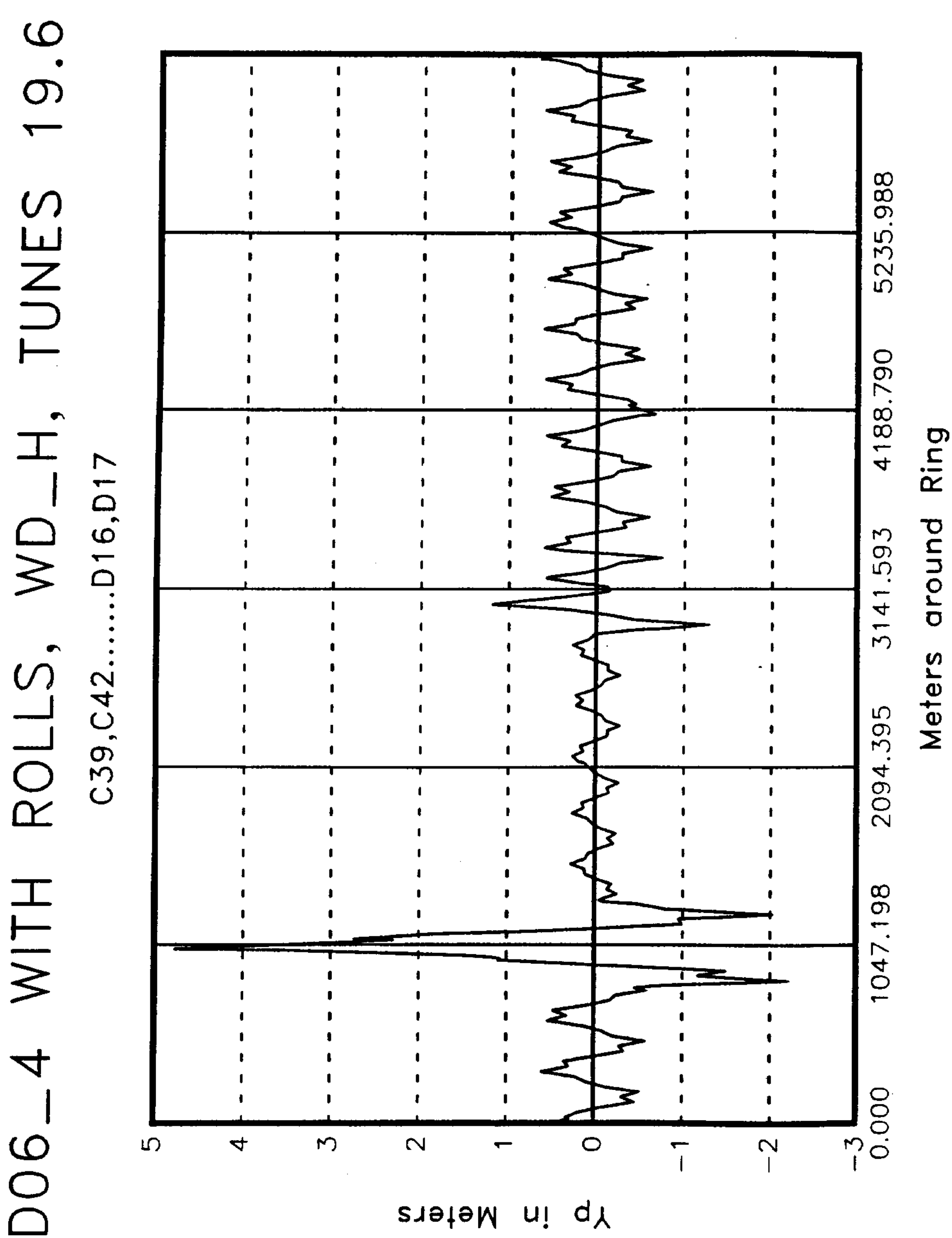

D06_4 WITH ROLLS, WD_H, TUNES 19.6
C39,C42.......D16,D17
Yp in Meters
5
4
3
2
1
0
−1
−2
−3
0.000
1047.198
2094.395
3141.593
4188.790
5235.988
Meters around Ring

Figure 17

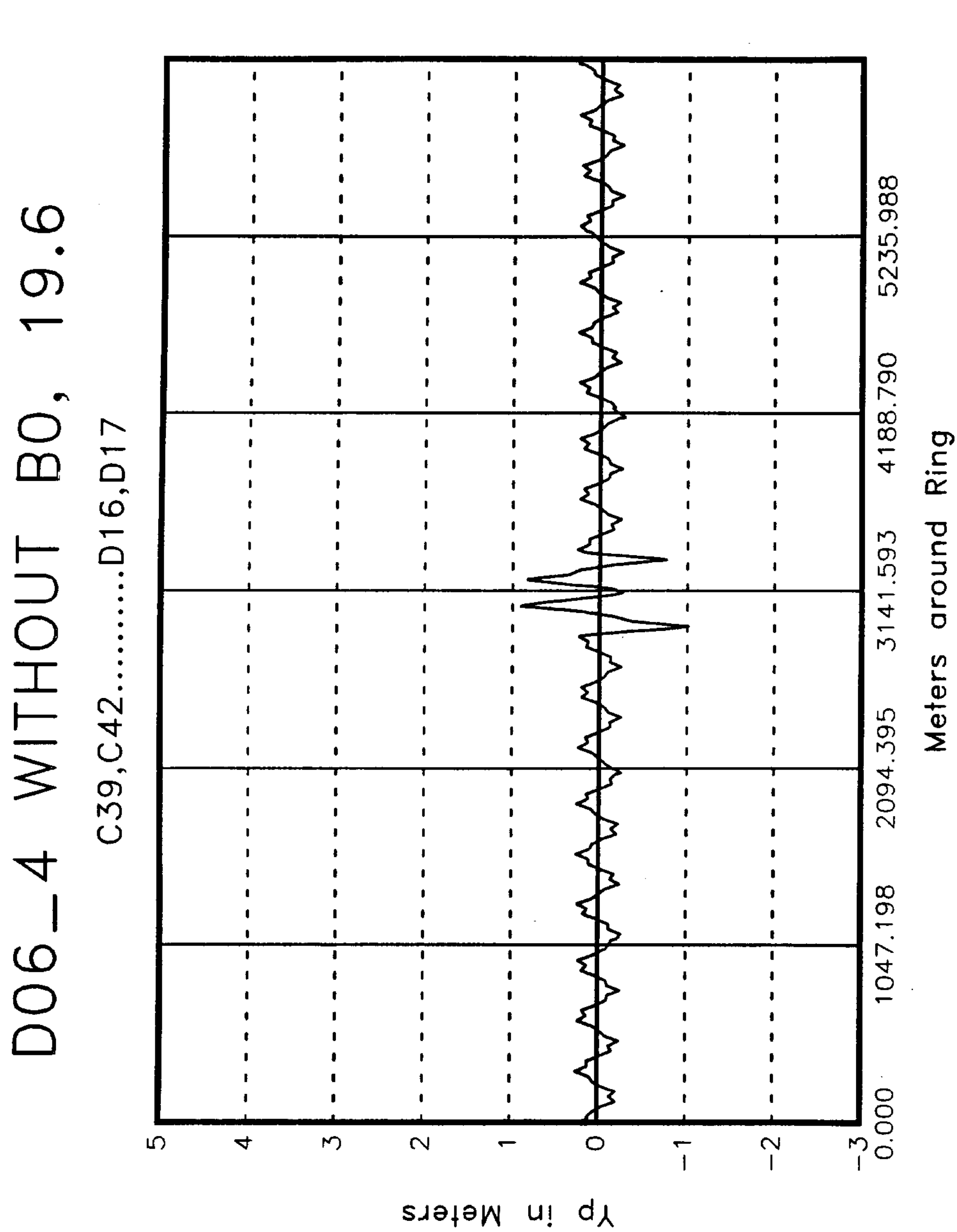

D06_4 WITHOUT B0, 19.6
C39,C42.........D16,D17
5
4
3
2
1
0
−1
−2
−3
Yp in Meters
0.000
1047.198
2094.395
3141.593
4188.790
5235.988
Meters around Ring

Figure 18

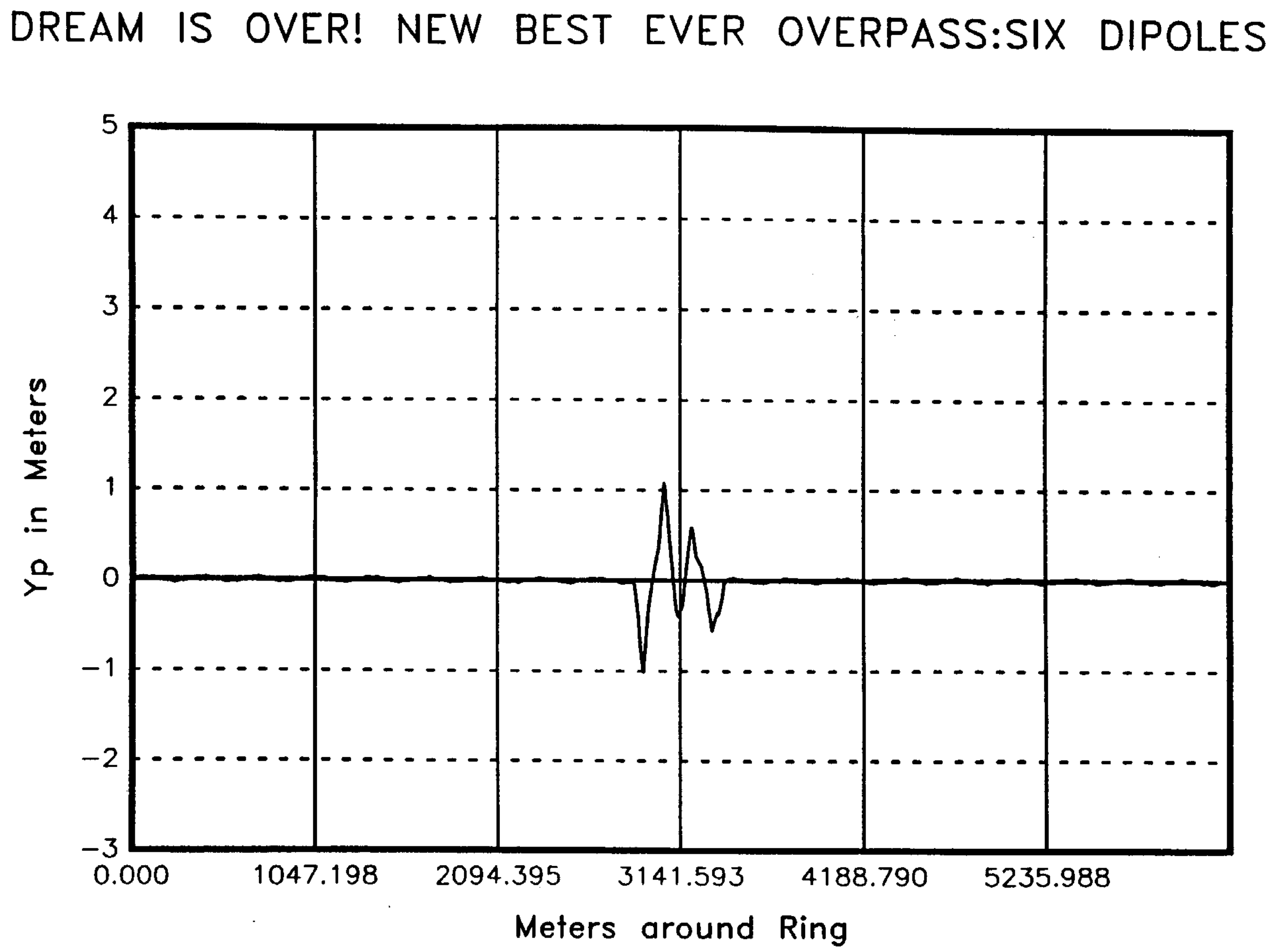

DREAM IS OVER! NEW BEST EVER OVERPASS:SIX DIPOLES
Yp in Meters
5
4
3
2
1
0
−1
−2
−3
0.000
1047.198
2094.395
3141.593
4188.790
5235.988
Meters around Ring

Figure 19

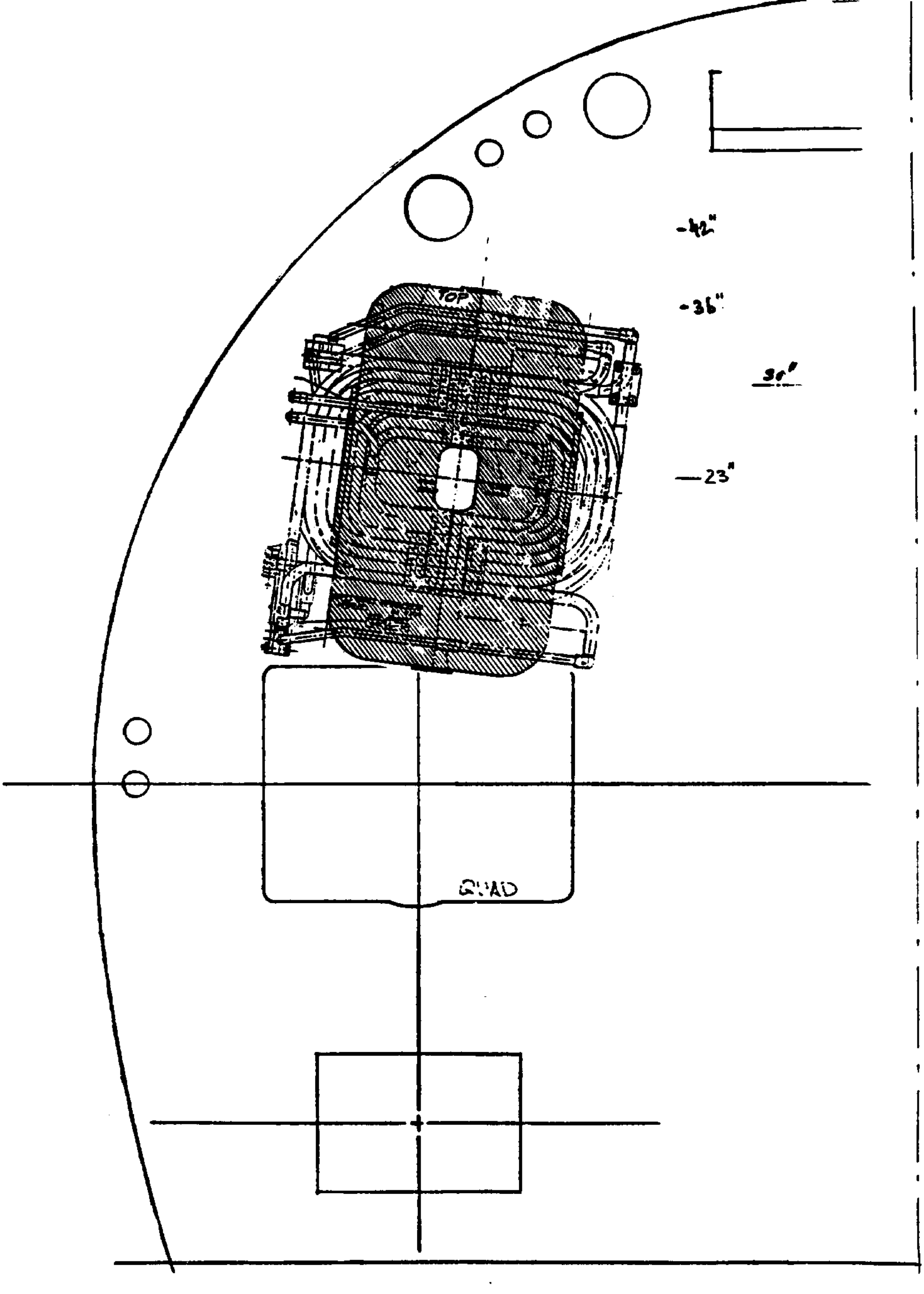


Figure 20

Calculated values of the proton and antiproton dispersion mismatch (ϵ/ϵ_0 where ϵ is the vertical emittance) between the Main Ring and the Tevatron in the present situation and with the new DO overpass when the tune is 19.6 are presented in TABLE 2.

TABLE 2

DISPERSION MISMATCH BETWEEN THE MAIN RING AND TEVATRON

	PRESENT	WITH NEW DO OVERPASS AND WITH 19.6 TUNE
PROTONS	2.42	1.16
ANTIPR.	2.42	1.16